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3D model of magnetic fields evolution in dwarf irregular galaxies

Hubert Siejkowski[1], Marian Soida[1], Katarzyna Otmianowska-Mazur[1], Michał Hanasz[2] and Dominik J. Bomans[3]

[1]Astronomical Observatory, Jagiellonian University, ul. Orla 171, 30-244 Kraków, Poland
email: h.siejkowski@oa.uj.edu.pl

[2]Torun Centre for Astronomy, Nicolaus Copernicus University, 87-148 Toruń/Piwnice, Poland

[3]Astronomical Institute of Ruhr-University Bochum, Univeristatsstr. 150/NA7, D-44780 Bochum, Germany

Abstract.
Radio observations show that magnetic fields are present in dwarf irregular galaxies (dIrr) and its strength is comparable to that found in spiral galaxies. Slow rotation, weak shear and shallow gravitational potential are the main features of a typical dIrr galaxy. These conditions of the interstellar medium in a dIrr galaxy seem to unfavourable for amplification of the magnetic field through the dynamo process. Cosmic-ray driven dynamo is one of the galactic dynamo model, which has been successfully tested in case of the spiral galaxies. We investigate this dynamo model in the ISM of a dIrr galaxy. We study its efficiency under the influence of slow rotation, weak shear and shallow gravitational potential. Additionally, the exploding supernovae are parametrised by the frequency of star formation and its modulation, to reproduce bursts and quiescent phases. We found that even slow galactic rotation with a low shearing rate amplifies the magnetic field, and that rapid rotation with a low value of the shear enhances the efficiency of the dynamo. Our simulations have shown that a high amount of magnetic energy leaves the simulation box becoming an efficient source of intergalactic magnetic fields.

1. Introduction

Dwarf irregular galaxies have relatively simple structure. They are smaller, less massive and have lower luminosity than spirals and ellipticals. Their rotation speed is very low and the rotation curve could be very complex (e.g. NGC 4449). The structure of a galaxy is often disturbed by a strong burst of star formation. Weak gravitational potential and slow rotation cause that supernovae explosions can substantially influence the gas distribution and global velocity pattern. Energy injected by a starbursting events is enough to drive a gas outflow from a dwarf galaxy. Together with gas also metals and magnetic fields are transported.

Radio observations (Chyży et al. 2000, 2003; Kepley et al. 2010; Klein et al. 1991, 1992) show that dIrr galaxies can have relatively strong magnetic fields. The typical total magnetic field strength is 5–15 μG with a uniform component about 5 μG. The observed magnetic fields suggest that a dynamo process should operate in these galaxies. We investigate the cosmic-ray driven dynamo model in the environment of a typical dwarf irregular galaxy.

2. Model description and initial setup

The CR-driven dynamo model consists of the following elements based on Hanasz et al. (2006) and references therein. We assume:

- the cosmic ray component described by the diffusion-advection transport equation and we adopt anisotropic diffusion;
- localized sources of CR, i.e. random explosions of supernovae in the disk volume. The cosmic ray input of individual SN remnant is 10% of the canonical kinetic energy output (10^{51} erg);
- resistivity of the ISM to enable the dissipation of the small-scale magnetic fields (see Hanasz & Lesch 2003). In the model, we apply the uniform resistivity and neglect the Ohmic heating of gas by the resistive dissipation of magnetic fields;
- shearing boundary conditions, tidal and Coriolis forces;
- realistic vertical disk gravity following the model by Ferrière (1998) with rescaled disk and halo masses by one order of magnitude.

The 3D cartesian domain size is 0.5 kpc $\times$ 1 kpc $\times$ 8 kpc in x, y, z coordinates corresponding to the radial, azimuthal, and vertical directions, respectively, with a grid size $(20\ \mathrm{pc})^3$. The boundary conditions are sheared-periodic in x, periodic in y, and outflow in z direction. The positions of SNe are chosen randomly with a uniform distribution in the xy plane and a Gaussian distribution in the vertical direction. In addition, the SNe activity is modulated during the simulation. The applied value of the perpendicular CR diffusion coefficient is $K_\perp = 10^3\ \mathrm{pc}^2\ \mathrm{Myr}^{-1}$ and the parallel one is $K_\parallel = 10^4\ \mathrm{pc}^2\ \mathrm{Myr}^{-1}$ (see Hanasz et al. 2009). The initial state of the system represents the magnetohydrostatic equilibrium with the horizontal, purely azimuthal magnetic field with $p_{mag}/p_{gas} = 10^{-4}$.

3. Results

3.1. *Rotation and shear*

We studied dependence of the magnetic field amplification on the parameters describing the rotation curve, namely, the shearing rate q and the angular velocity Ω. The evolution in the total magnetic field energy E_B and total azimuthal flux B_ϕ for different values of Ω is shown in Fig. 1, left and right panel, respectively. Models with higher angular velocities, starting from 0.03 Myr^{-1}, initially exhibit exponential growth of the magnetic field energy E_B till 1 200 Myr followed by a saturation. The saturation values of the magnetic energy for these three models are similar and E_B exceeds the value 10^4 in the normalized units. The magnetic energy in the models R.01Q1† (slow rotation, moderate shear) and R.02Q1 (slow rotation, moderate shear) grows exponentially during the whole simulation and does not reach the saturation level. The total azimuthal magnetic flux evolution (Fig. 1, right) shows that a higher angular velocity leads to a higher amplification. There is no amplification in model R.01Q1.

3.2. *Star formation*

We checked how the frequency and modulation of SNe influence the amplification of magnetic fields. The evolution in total magnetic field energy and total azimuthal flux for different supernova explosion frequencies are shown in Fig. 2. The total magnetic energy evolution for all models is similar, but the differences are apparent in the evolution of azimuthal flux. The most efficient amplification of B_ϕ appears for SF10R.03Q.5 (medium SFR, moderate rotation, low shear) and SF10R.03Q1 (moderate shear), and for other

† Letter R stands for angular velocity (rotation) given in Myr^{-1}, Q shearing rate ($q = -d\ln\Omega/d\ln R$) and SF for star formation given in $\mathrm{kpc}^{-2}\ \mathrm{Myr}^{-1}$.

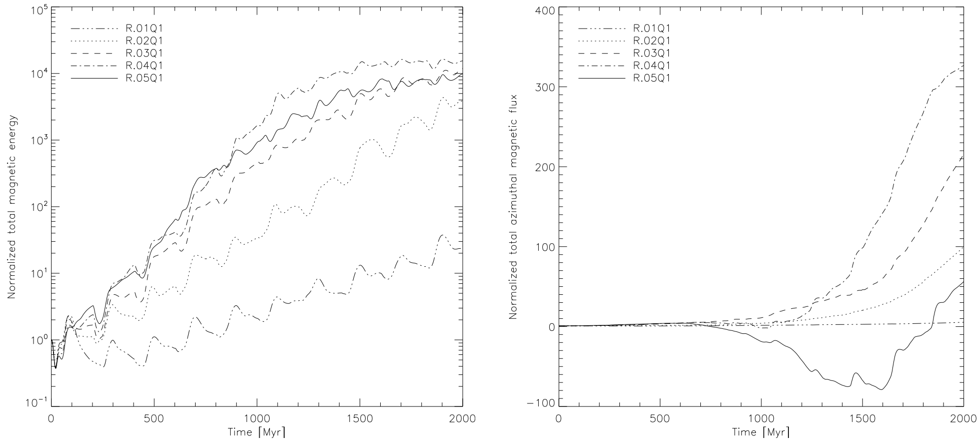

Figure 1. Evolution of the total magnetic energy E_B (left panel) and the total azimuthal flux B_ϕ (right) for models with different rotation. Both quantities are normalized to the initial value.

models the process is less efficient. In addition, for models SF30R.03Q.5 (high SFR, low shear) and SF30R.03Q1 (high SFR, moderate shear), we observe a turnover in magnetic field direction. The results suggest that the dynamo requires higher frequencies of supernova explosions to create more regular fields, although, if the explosions occur too frequently because of a strong wind transporting magnetic field out of the disk.

3.3. *Outflow of magnetic field*

To measure the total production rate of the magnetic field energy during the simulation time, we calculated the outflowing E_B^{out} through the xy top and bottom domain boundaries. To estimate the magnetic energy loss, we computed the vertical component of the Poynting vector. Its value is computed in every cell belonging to the top and bottom boundary planes and then integrated over the entire area and time. For models with a low dynamo efficiency most of the initial magnetic field energy is transported out of the simulation box. In some cases (i.e., all models except R.01Q0 and R.05Q0 with zero shear), we find that the energy loss E_B^{out} is comparable to the energy remaining inside the domain $\bar{E}_B^{end}$. In these models, the ratio $E_B^{out}/\bar{E}_B^{end}$ varies from 0.03 to 0.96 and is highly dependent on the supernova explosion frequency. The results show that the outflowing magnetic energy is substantial (see Siejkowski et al. 2010) suggesting, that irregular galaxies can be efficient sources of intergalactic magnetic fields.

4. Conclusions

We have described the evolution of the magnetic fields in irregular galaxies in terms of a cosmic-ray driven dynamo (Siejkowski et al. 2010). The amplification of magnetic fields have been studied under different conditions characterized by the rotation curve (the angular velocity and the shear) and the supernovae activity (its frequency and modulation) typical for irregular galaxies. We have found that:

- in the presence of slow rotation and weak shear in irregular galaxies, the amplification of the total magnetic field energy is still possible;
- shear is necessary for efficient action of CR-driven dynamo, but the amplification itself depends weakly on the shearing rate;
- higher angular velocity enables a higher efficiency in the CR-driven dynamo process;

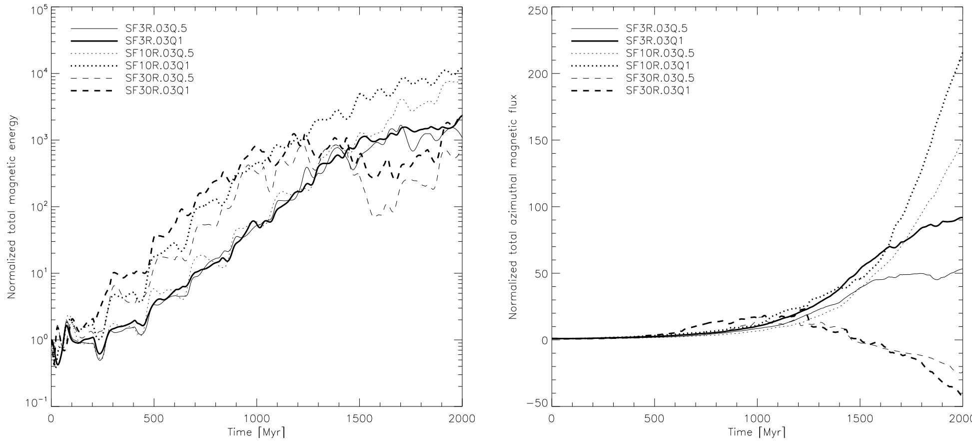

Figure 2. Evolution of the total magnetic energy E_B (left panel) and the total azimuthal flux B_ϕ (right) for models with different supernova explosion frequency and shearing rate. Both quantities are normalized to the initial value.

- the efficiency of the dynamo process increases with SNe activity, but excessive SNe activity reduces the amplification;
- for high SNe activity and rapid rotation, the azimuthal flux reverses its direction;
- the outflow of magnetic field from the disk is high, suggesting that dIrr galaxies may magnetize the intergalactic medium as predicted by Kronberg et al. (1999) and Bertone et al. (2006).

The performed simulations indicate that the CR-driven dynamo can explain the observed magnetic fields in dwarf irregular galaxies. In future work we plan to determine the influence of other ISM parameters and perform global simulations of these galaxies.

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